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We propose a new measurement to be performed at the Tevatron which can be decisive to distinguish between Pomeron-based and soft color interaction models of hard diffractive scattering.

**1. Introduction** The hard diffraction phenomena revealed at HERA [1] has put a new light on the longlasting interrogation concerning the nature of elastic and diffractive scattering in strong interactions. The question is whether or not this interaction is mediated by the exchange of an object, the Pomeron, with properties of a well-defined hadronic particle or, at least, of a well-defined Regge pole appearing in all diffractive processes.

In this context, in a first class of models initiated in Ref. [2] hard diffraction is explained by deep inelastic scattering (DIS) on the Pomeron, in a similar way as DIS on the proton leads to non-diffractive events. In a second class of models, diffractive events are not distinguished from non-diffractive ones, except by a soft color interaction (SCI) [3] (or Lund string reconnection) which may restore color singlet exchange. In this second approach, the notion of a Pomeron is *a priori* absent.

In the present paper we show that the forward detector apparatus in the DØ experiment at the Tevatron, Fermilab, has the potential to discriminate between the predictions of the two approaches in hard “double” diffractive production, e.g. of centrally produced dijets, by looking to the azimuthal distributions of the outgoing proton and antiproton with respect to the beam direction. This measurement relies on tagging both outgoing particles in roman pot detectors installed by the D0 experiment. We show from a Monte-Carlo simulation that this measurement can give significant results during the present RUN II at the Tevatron.

**2. Theoretical framework** The discriminative potential of our proposal takes its origin in the factorization breaking properties which were already observed at the Tevatron. Both classes of models have a radically different explanation for this factorization breaking, cf. Fig.1.

The Pomeron hypothesis implies the Regge factorization property, the same Pomeron vertex can be used to compute different diffractive processes, e.g. the proton vertex at HERA and the Tevatron. In fact, hard diffraction at the Tevatron, e.g. diffractive dijet production, has revealed strong violations of factorization in hard diffraction [4]. The explanation given to this factorization breaking is the occurrence of large corrections from the survival probabilities, which is the probability to keep a diffractive event signed either by tagging the proton in the final state or by requiring the existence of a rapidity gap in the event.

The soft scattering between incident particles tends to mask the genuine hard diffractive interactions at hadronic colliders. The formulation of this correction [5] to the scattering amplitude  $\mathcal{A}$  consists in considering a gap survival probability (*SP*) function  $S$  such that

$$\mathcal{A}(p_{T1}, p_{T2}, \Delta\Phi) = \{1 + \mathcal{A}_{SP}\} * \mathcal{A}^h \equiv S * \mathcal{A}^h = \int d^2\mathbf{k}_T \mathcal{S}(\mathbf{k}_T) \mathcal{A}^h(\mathbf{p}_{T1} - \mathbf{k}_T, \mathbf{p}_{T2} + \mathbf{k}_T), \quad (1)$$

where  $\mathbf{p}_{T1,2}$  are the transverse momenta of the outgoing  $p, \bar{p}$  and  $\Delta\Phi$  their azimuthal angle separation. In our study the hard scattering amplitude  $\mathcal{A}^h$  is obtained from the factorizable Pomeron model POMWIG [6].  $\mathcal{A}_{SP}$  is the soft scattering amplitude. In our simulations we used two different models, either the two-channel eikonal *model 1* [7] (elastic and low-mass diffraction) or only the elastic channel *model 2* as proposed for hard diffraction in [8].

By contrast with Pomeron models, soft color interaction models are by nature non factorizable. As described in Fig.1, the initial hard interaction is the generic standard QCD dijet production, accompanied by the full parton shower. Then, a phenomenological soft color interaction is assumed to modify the overall color content, allowing for a color singlet exchange and thus diffraction. This process is evaluated using a Monte-Carlo simulation [9] which we used in our study.

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### 3. The DØ Forward Proton Detector

The Forward Proton Detector (FPD) [11] installed by the DØ collaboration provides a unique opportunity to measure the azimuthal angle  $\Phi$  of the outgoing protons and antiprotons and thus to test the dependence of diffractive events at the Tevatron on  $\Delta\Phi$  between the tagged protons and antiprotons.

The FPD consists of eight momentum spectrometers located close to a quadrupole magnet of the Tevatron (in short *quadrupole* spectrometers) and one spectrometer close to a dipole magnet (in short *dipole* spectrometer), see Fig.2. Four quadrupole spectrometers are located on the outgoing proton side, the other four on the antiproton side. On each side, the quadrupole spectrometers are placed both in the inner (Q-IN), and outer (Q-OUT) sides of the accelerator ring, as well as in the upper (Q-UP) and lower (Q-DOWN) directions. They provide almost full coverage in  $\Phi$ . The dipole spectrometer, marked as D-IN in Fig.2, is placed in the inner side of the ring in the direction of outgoing antiprotons.

Each spectrometer allows one to reconstruct the trajectories of outgoing protons and antiprotons near the beam pipe and thus to measure their energies and scattering angles. Spectrometers provide high precision measurement in  $t = -p_T^2$  and  $\xi = 1 - P'/E$  variables, where  $P'$  and  $p_T$  are the total and transverse momenta of the outgoing proton or antiproton, and  $E$  is the beam energy. The dipole detectors show a good acceptance down to  $t = 0$  for  $\xi > 3.10^{-2}$  while the quadrupole detectors are sensitive to outgoing particles down to  $|t| = 0.6 \text{ GeV}^2$  for  $\xi < 3.10^{-2}$ . This allows to obtain a good acceptance for high mass objects diffractively produced in the DØ main detector. For our analysis, we use a full simulation of the FPD acceptance in  $\xi$  and  $t$  [12].

Two sorts of combinations are possible with the FPD. In the first one, the dipole detector on the antiproton side can be combined with a quadrupole detector on the proton side. This combination gives *asymmetric* cuts on  $t$  due to the different acceptance of the two kinds of spectrometers. The good coverage in  $\Phi$  of the four quadrupole spectrometers enables to measure the diffractive cross section as a function of  $\Delta\Phi$  between the outgoing protons and antiprotons. In the second configuration, quadrupole detectors can be used on both sides which allows to get *symmetric* cuts on  $t$ .

### 4. $\Delta\Phi$ dependence of the double diffractive cross section

In Fig.3, we give the profile of the  $\Delta\Phi$  dependence of the diffractive cross section. As an example, we require events with two jets with a transverse momentum greater than 5 GeV and tagged proton and antiproton. The SCI model [9] has been produced using a modified version of PYTHIA [10]. The Pomeron model has been generated using POMWIG [6] and the Pomeron structure function measured by the H1 Collaboration [1] interfaced with the two models for the survival probabilities described in Section 2.

We first display (upper curves) the result for asymmetric cuts in  $t$  ( $|t_p| > 0.6$ ,  $|t_{\bar{p}}| > 0.1 \text{ GeV}^2$ ). We notice that the result for SCI is independent on  $\Delta\Phi$  whereas the POMWIG results with survival probabilities show less events at high  $\Delta\Phi$  by a factor of about 5. Both survival probability models exhibit strong  $\Delta\Phi$  dependence with similar shape but with different relative normalization. The lower plots in Fig. 3 show the results for symmetric cuts on  $t$  ( $|t_{p,\bar{p}}| > 0.5 \text{ GeV}^2$ ). The difference between SCI and POMWIG models is even larger in this configuration, and goes up to a factor 30. Both survival probability models show similar behavior but the position of the minimum in  $\Delta\Phi$  is slightly shifted.

### 5. Proposed measurement at the Tevatron

The first measurement we propose, and which can be performed even at low luminosity, directly benefits from the FPD configuration, i.e. from the structure in  $\Phi$  of the detector itself. We suggest to count the number of events with tagged  $p$  and  $\bar{p}$  for different combinations of FPD spectrometers. For this purpose, we define the following configurations for dipole-quadrupole tags (see Fig. 2): same side (corresponding to D-IN on  $\bar{p}$  side and Q-IN on  $p$  side and thus to  $\Delta\Phi < 45$  degrees), opposite side (corresponding to D-IN on  $\bar{p}$  side and Q-OUT on  $p$  side, and thus to  $\Delta\Phi > 135$  degrees), and middle side (corresponding to D-IN on  $\bar{p}$  side and Q-UP or Q-DOWN on  $p$  side and thus to  $45 < \Delta\Phi < 135$  degrees). We define the same kinds of configurations for quadrupole-quadrupole tags (for instance, the same side configuration corresponds to the sum of the four possibilities: both protons and antiprotons tagged in Q-UP, Q-DOWN, Q-IN or Q-OUT).

In Table 1, we give the ratios  $1/2 \times \text{middle}/\text{same}$  and  $\text{opposite}/\text{same}$  (*middle* is divided by 2 to get the same domain size in  $\Phi$ ) for the different models. In order to obtain these predictions, we used the full acceptance in  $t$  and  $\xi$  of the FPD detector [12]. Moreover we computed the ratios for two different tagging configurations for the symmetric and asymmetric cuts in  $t$  described above, namely for  $\bar{p}$  tagged in dipole detectors, and  $p$  in quadrupoles, or for both  $p$  and  $\bar{p}$  tagged in quadrupole detectors.

In Table 1, we observe that the  $\Delta\Phi$  dependence of the event rate ratio for the SCI model is weak, whereas for the POMWIG models the result show important differences specially when both  $p$  and  $\bar{p}$  are tagged in quadrupole

Configuration	model	middle/same	opposite/same
Quad. + Dipole	SCI	1.3	1.1
	Pomeron Model 1	0.36	0.18
	Pomeron Model 2	0.47	0.20
Quad. + Quad.	SCI	1.4	1.2
	Pomeron Model 1	0.14	0.31
	Pomeron Model 2	0.20	0.049

TABLE I: *Predictions for a proposed measurement of diffractive cross section ratios in different regions of  $\Delta\Phi$  at the Tevatron* (see text for the definition of middle, same and opposite). The first (resp. second) measurement involves the dipole and one quadrupole detectors (resp. quadrupole detectors only) corresponding to asymmetric (resp. symmetric) cuts on  $t$ .

detectors. This measurement can be performed even at low luminosity. Indeed, the expected number of events for POMWIG for  $10 \text{ pb}^{-1}$  is respectively about  $10^3$  (resp. about 25) for the dipole-quadrupole (resp. quadrupole-quadrupole) configurations if two jets with a transverse momentum greater than 5 GeV are required. This corresponds to a very low luminosity at the Tevatron (about 1 week of running now), and thus it is possible to increase the cut on the jet  $p_T$  to perform this study.

The measurement can also be performed using vector mesons ( $J/\Psi$  for instance), or even  $W$  and  $Z$  at higher luminosity. With more luminosity, we also propose to measure directly the differential  $\Delta\Phi$  dependence between the outgoing protons and antiprotons using the good coverage of the quadrupole detectors in  $\Phi$  which will allow to perform a more precise test of the models.

## 6. Conclusion

To summarize, we propose a new measurement to be performed at the Tevatron which can be decisive to distinguish between Pomeron-based and soft color interaction models of hard diffractive scattering. The difference in azimuthal angle between the leading outgoing proton and antiproton in hard double diffractive interactions is found to be a discriminating observable to distinguish between these two classes of models and thus to investigate the nature of the Pomeron. We showed that this measurement can be performed with the present DØ detector.

If one finds a strong  $\Delta\Phi$  dependence, the soft color interaction approach would be disfavoured unless new important changes in the way PYTHIA deals with non-perturbative color reconnection are introduced. On the other hand if the  $\Delta\Phi$  dependence is weak, it would mean that Pomeron concept has to be revised.

The measurement is also fundamental to obtain precise predictions for diffractive cross section at the LHC, such as the cross section for diffractive Higgs boson production.

## Acknowledgments

We thank Rikard Enberg for useful discussions and Jorge Barreto for providing the simulated acceptance of the FPD.

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- [1] H1 Collab., C. Adloff et al., *Z. Phys. C* **76** (1997) 613; ZEUS coll., *Eur. Phys. J. C* **1** (1998) 81.
- [2] G. Ingelman, P. Schlein, *Phys. Lett. B* **152** (1985) 256.
- [3] A. Edin, G. Ingelman and J. Rathsman, *Phys. Lett. B* **366**, (1996) 371; R. Enberg, G. Ingelman, N. Timneanu, *Phys. Rev. D* **64** (2001) 114015, and references therein.
- [4] CDF Collab. *Phys. Rev. Lett.* **84** (2000) 5043; C. Royon, L. Schoeffel, J. Bartels, H. Jung, R. Peschanski, *Phys. Rev. D* **63** (2001) 074004.
- [5] J. D. Bjorken, *Phys. Rev. D* **47**, (1993) 101; E. Gotsman, E. Levin and U. Maor, *Phys. Lett. B* **438** (1998), 229; A. B. Kaidalov, V. A. Khoze, A. D. Martin and M. G. Ryskin, *Eur. Phys. J. C* **21** (2001) 521.
- [6] B. Cox, J. Forshaw, *Comput. Phys. Commun.* 144 (2002) 104.
- [7] V. A. Khoze, A. D. Martin and M. G. Ryskin, *Eur. Phys. J. C* **18** (2000) 167, *Eur. Phys. J. C* **24** (2002) 581.
- [8] A. Bialas, *Acta Phys. Polon. B* **33** (2002) 2635; A. Bialas, R. Peschanski, *Phys. Lett. B* **575** (2003) 30.
- [9] We used the Pythia SCI Monte Carlo program described in <http://www3.tsl.uu.se/theMC/scigal/>

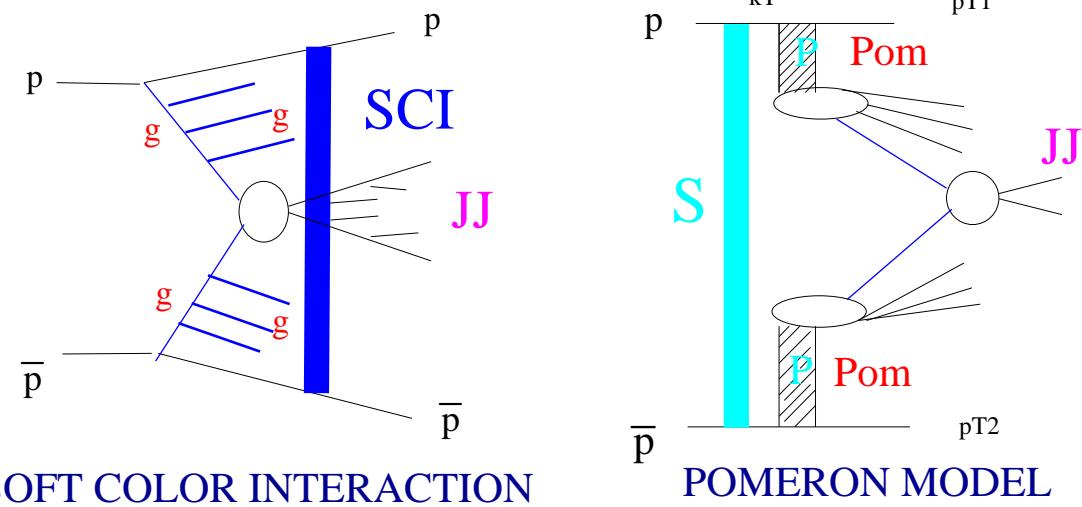


FIG. 1: Description of the SCI and Pomeron models for dijet (JJ) diffractive production. Left scheme: SCI model; the standard QCD dijet production is modified by the soft color interaction (SCI). Right scheme: Pomeron model; the factorized double Pomeron dijet production is corrected for the initial soft interaction  $S$ , see text.

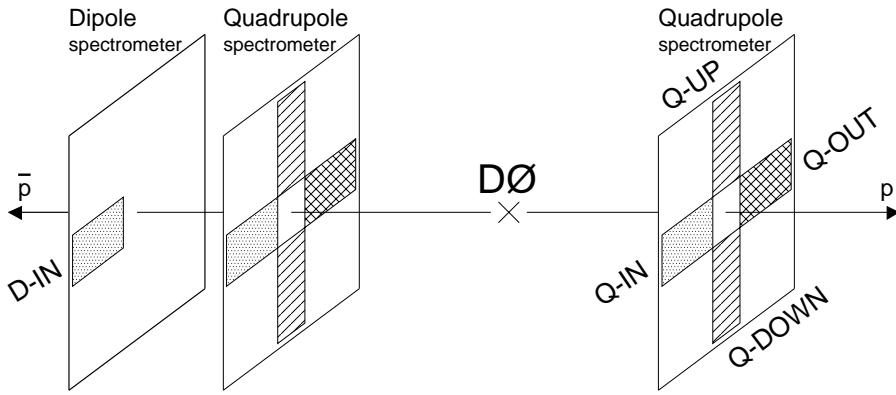


FIG. 2: Schematic view of the FPD detector. We show the positions of the dipole and quadrupole spectrometers with respect to the main DØ detector. The quadrupole detectors on  $p$  and  $\bar{p}$  sides consist of 4 spectrometers called Q-UP, Q-DOWN, Q-IN, Q-OUT, and the dipole detector on  $\bar{p}$  side only of one spectrometer D-IN.

- [10] T. Sjöstrand, P. Edén, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin, *Computer Phys. Commun.* **135** (2001) 238
- [11] *Proposal for a Forward Proton Detector at DØ*, DØ Collaboration (1997), Proposal P-900 to FERMILAB PAC.
- [12] J. Barreto, *Proceedings of the 5th Small- $x$  and Diffraction Workshop*, Fermilab, Sept. 17-20 2003; J. Barreto, J. Montanha, DØ note 3790.

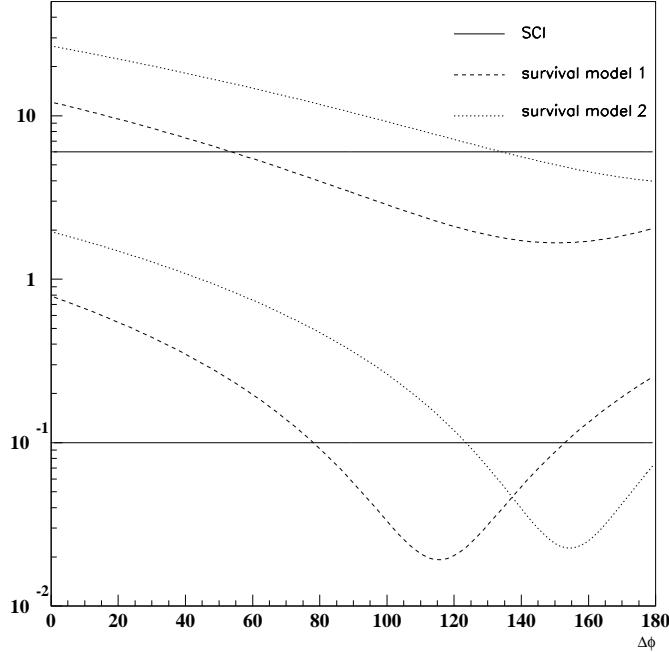


FIG. 3: *Predicted profile of  $\Delta\Phi$  between the outgoing  $p$  and  $\bar{p}$  for SCI and Pomeron-based models.* The upper curves are for asymmetric cuts in  $t$  ( $|t_p| > 0.6, |t_{\bar{p}}| > 0.1 \text{ GeV}^2$ ) and the lower ones for symmetric cuts on  $t$  ( $|t_{p,\bar{p}}| > 0.5 \text{ GeV}^2$ ). Solid lines: SCI model, dashed lines: Pomeron model 1, and dotted lines: Pomeron model 2 (see text). Note that for Pomeron models the minimum is close to back-to-back proton and antiproton for asymmetric cuts while it is around 130 degrees for symmetric cuts.